DESIGN OF A GROUND BASED SNOWPACK ENHANCEMENT PROGRAM

USING LIQUID PROPANE

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Abstract - The design of a winter snowpack augmentation program utilizing liquid propane as the seeding agent is described. The program has been designed utilizing results from the Sierra Cooperative Pilot Project(SCPP). Observations from SCPP showed that the bulk of the supercooled liquid water (SLW) in winter storms over the Sierra occurs within the first kilometer above the barrier at temperatures between 0 and -10°C and in concentrations of 0.05 to 0.2 g/m^3. Mountain-top icing stations within the Feather River drainage indicate that icing occurs with a mean temperature near -3°C. These results imply the need for a seeding agent capable of converting the SLW to ice crystals at fairly warm temperatures and be released remotely from the ground. Liquid propane meets these requirements.

The design calls for two 2175 liter tanks of propane at each site. Remote operation will be via radio to an on-site micro-processor. Site seperation will be every two kilometers along the crest of the Sierra above the Middle Fork Feather. Tanks will be flown in by helicopter in the fall and removed early in the spring. Three sites will be used the first year for test purposes. The release rate will be 10 liters/hr per dispenser. Multiple atmospheric soundings, telemetered mountain-top icing data, and a simple diagnostic targeting model will be used for real-time decision making. Initial estimates are that suitable clouds exist from 200 to 400 hours per winter season. Based on propane activitation levels, cloud liquid water content, and crystal growth times, 12,300 m^3 per dispenser per hour is possible.

1.0 INTRODUCTION

Cloud seeding to increase winter snowpack has been conducted since the early 1950's in several basins in the Sierra Nevada. With the discovery by Drs. Schaefer and Vonnegut that additional ice crystals could be generated in clouds containing supercooled liquid water, an immediate attempt was made to transfer this capability into increasing wintertime snowpacks in the Sierra. This design builds on the assumption that some clouds existing in winter storms over the Sierra Nevada contain insufficient ice-forming nuclei, or that the nuclei are unable to convert cloud condensate, produced by the orographic lift of the barrier, soon enough to remove all the cloud water. Thus that portion of cloud water which exists at temperatures below 0 °C, and is therefore supercooled, is lost to the precipitation process to the lee of the mountain. By proper application of glaciogenic seeding material, an attempt is made to convert this cloud condensate to ice before it passes over the crest. A recent paper by Reynolds (1988) reviews these principles and the current thinking on the feasibility of winter snowpack enhancement. The California Department of Water Resources (DWR) has contracted with the Bureau of Reclamation to design and implement a program to seed the Middle Fork of the Feather River basin in the northern Sierra Nevada to increase runoff to Oroville Reservoir, Fig. 1.. This paper describes the results of this study.

From 1976 through the 1986-87 winter season the Bureau of Reclamation sponsored the Sierra Cooperative Pilot Project (SCPP). The purpose of this program was to further refine when and where to seed clouds in the Sierra Nevada for winter snowpack enhancement and to determine the magnitude of those increases (Reynolds and Dennis, 1986). SCPP achieved two major accomplishments. The first was in the application of observing equipment for determining the spatial and temporal variability of supercooled liquid water in clouds over the Sierra Nevada. The second was developing diagnostic models for determining when and where to seed this supercooled liquid for increasing precipitation within intended target areas. These results were major inputs to the formulation of this design. In addition, several remote meteorological stations providing information on the wind, temperature, and occurrence of rime icing were established in the Feather River basin at high elevation sites. These data provided valuable additional information utilized in this design.

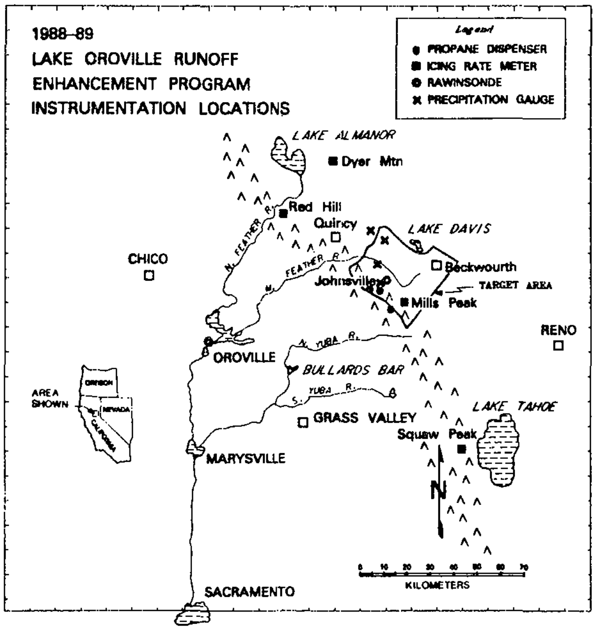

Figure 1 *Site map and instrumentation locations for the Lake Oroville Runoff Enhancement Program.*

2.0 SEEDING HYPOTHESIS

2.1 Liquid Water Distributions

As has been mentioned, certain cloud systems which occur within winter storms over the Sierra Nevada are inefficient in removing all the available cloud water before the air passes over the barrier and the cloud water is evaporated. It has been found by the SCPP that this cloud water available for removal by seeding is concentrated in the lowest 1000 m above the barrier, at temperatures between 0 and -10 °C and at concentrations of 0.05-0.2 g/m^3. This information was derived by application of a remote sensing device (microwave radiometer) near the crest of the Sierra (Heggli & Rauber, 1988). Further refinement of the occurrence of liquid water at mountain-top level has been made from installation of an icing rate meter positioned at mountain-top. Results of observations from three mountaintop icing stations (see Fig. 1 for locations) are shown in Fig. 2. This shows the cumulative frequency of icing (i.e. supercooled water) atop Squaw Peak in the central Sierra and Dyer Mountain (DMT) and Red Hill (RDH) in the Feather River basin as a function of temperature. Note the distribution for all three stations is skewed to the warmer temperatures with a mode of 0 to -2 °C and a median value of -3 °C. The Squaw Peak data cover two winters, 1985-86 and 1986-87. The DMT and RDH data are from 15 November to 20 January 1986-87. (The temperature sensor on each station failed after 20 Jan.) These data indicate that when supercooled liquid water SLW is present near 2.0 - 2.6 km MSL it is at temperatures slightly below 0 °C, with the occurrence and magnitude of liquid water dropping off at the colder temperatures. Fig. 3 shows the total number of hours of icing at DMT and RDH for 1987-88. The monthly precipitation for the Feather River basin as a percentage of normal is also shown. The figure shows 419 hours of icing at Dyer Mountain and 186 hours at Red Hill from November 21, 1987 to April 30, 1988. Despite this year being a critically dry year, this data indicates substantial time available for seeding.

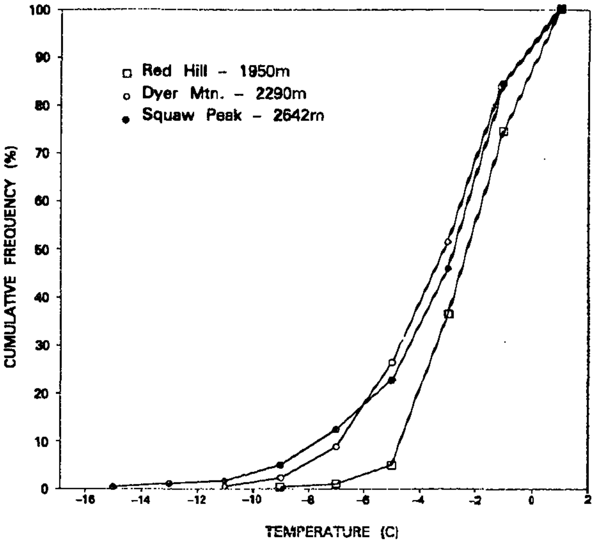

Figure 2 *Icing occurrence as a function of temperature for three mountain-top locations along the Sierra Nevada.*

3.2 Tapping the Available Supercooled Liquid Water

The icing data suggests the need for a seeding agent, active at converting supercooled droplets into ice crystals at temperatures between 0 and -5 °C, thus offering the opportunity for seeding many more events from the surface. Dry ice, or solid CO_2, has been shown to be an effective seeding agent at temperatures close to 0 °C and was used extensively on the SCPP. However, the only mechanism for adequate delivery is aerial release. Based on SCPP results, this is not as desirable a delivery mechanism due to limited dispersion within seedlines and difficulties in placing the aircraft within (SLW) regions necessary to adequately target the effects to the desired locations. However, a seeding agent does exist that is effective at producing ice crystals near 0 °C and can be remotely released at a ground site. This agent is liquid propane released as a fine spray. Vardiman et al. (1971) has fully documented the use of propane as a glaciogenic seeding agent for dispersing cold fog. The principle behind this production of ice crystals is that liquid propane, sprayed into the environment as a fine mist, vaporizes and rapidly chills the air to temperatures well below 0 °C. Figure 4 shows the cooling which takes place in the vicinity of the nozzle using a 38 l/hr dispensing rate. As temperatures approach -40 °C (-42 °C is the boiling point of propane) moisture rapidly condenses into many cloud droplets which immediately freeze and grow into tiny ice crystals. This condensation/freezing process is nearly simultaneous. Therefore, in looking at Fig. 4, ice crystal production will occur within 12-14 inches of the release point. Hicks and Vali (1973) and Kumai (1982) have determined through laboratory and field experimentation that the yield from the release of 1 gram of propane is 10^{11}-10^{12} ice crystals. This activity can be compared to other seeding agents commonly used, Fig. 5.

From the available data given above it is apparent that propane offers a very real potential as a seeding agent for increasing snowpack within the Sierra Nevada. Therefore, the task is to install the most efficient, remotely operated propane dispensing system positioned at altitudes within supercooled clouds and with exposures allowing rapid dispersion of the ice crystals produced.

3.3 Anticipated Effects with Propane

The release of propane within supercooled liquid water clouds at temperatures ≤-2 °C is expected to lead to the following results:

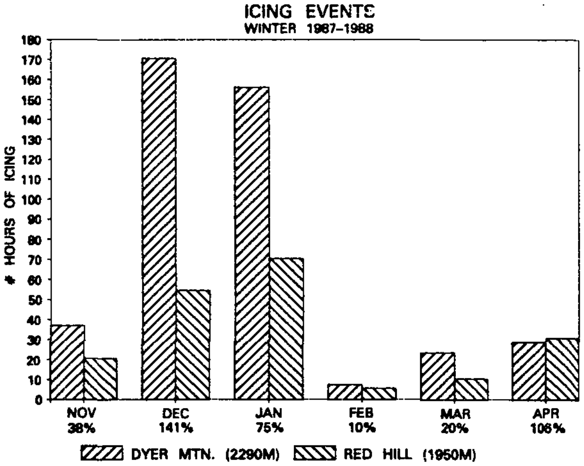

Figure 3 *Number of hours of icing within the Feather River Drainage for Dyer Mountain and Red Hill for the 1987-1988 winter season. Percentages below the month are the percent of normal precipitation for the Feather River basin.*

Within several feet of the nozzle, a high concentration of very small ice particles (<50 µm) will develop. Due to the turbulent flow at mountaintop levels the plume of ice crystals will disperse horizontally at a rate of 1-2 m s-1 downwind. The small crystals will be lifted into the cloud due to terrain induced vertical motions. These crystals will grow rather slowly at approximatly 0.5 µm/sec and should reach 200-300 µm within 5-10 min. Given these crystals will be compact plates or squatty columns (Hicks and Vali, 1972; Kumai, 1982; Deshler et al., 1987) they will rime rather rapidly in the presence of supercooled water and begin to fallout within the next 5 to 10 min. Given an average wind speed of 10 m/s, the crystals will initially begin to fallout 10 km downwind of the release point. This will vary with liquid water content, wind speed and the height of the underlying terrain. Those crystals that have not reached a size sufficient for fallout will continue downstream. It is anticipated that the bulk of the crystals will have fallen out within 60 min or 36 km downwind, again dependent on wind speed. With dispensing sites near the crest, the descent of air downwind of the crest will accelerate fallout but may also sublimate some of the smaller ice crystals. Therefore, a combination of critical dispenser placement and optimized seeding conditions will be needed to minimize this effect. This will be discussed in the following sections. It is calculated that each dispenser will produce approximately 12,500 m^3/hr under suitable cloud conditions.

In conclusion, propane satisfies many critical requirements for effective seeding in Sierra Nevada winter mountain clouds. First, the requirement that it be released in supercooled cloud eliminates the uncertainty of vertical transport to the -5 °C level or colder required by AgI. Liquid water can be confirmed by icing rate observations. [Aircraft seeding in the SCPP was performed almost exclusively to assure direct injection into clouds containing supercooled water]. Ground release assures a continuous source of nuclei during appropriate conditions.

3.4 Proposed Target Areas

Phase I will be a multi-year pilot program to confirm proper dispensing design, release rates, and functional performance under severe wind and rime icing conditions. Three dispensers will be placed on the Sierra crest, southwest of the primary target above 2100 m elevation. (Fig. 1).

A ground microphysics laboratory (Deshler, 1988) will be established at the Johnsville (JVL) ski area, Fig. 1. This ski area is just over 1500 m elevation and is approximately 5 km downwind of the dispensers. Therefore, it should be targeted with the most rapidly falling crystals during lighter wind conditions.

3.5 Propane Dispenser Design and Operation

The propane dispenser and site setup is shown in Fig. 6. The design and

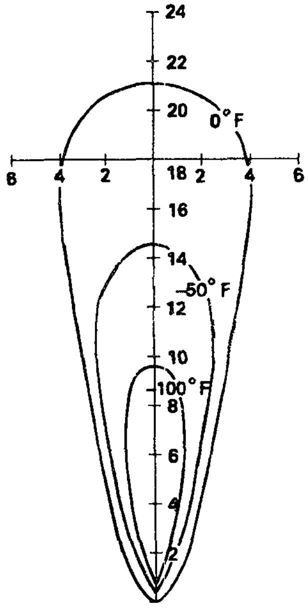

Figure 4 *Cooling as a function of distance (in.) from the nozzel from release of liquid propane at 38 l/hr. From Vardiman et al. (1971).*

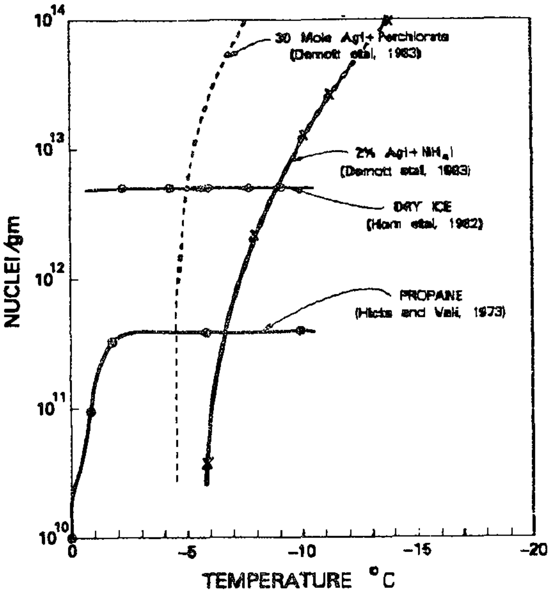

Figure 5 *Activity spectra of various glaciogenic seeding material as a function of temperature as available from the published literature.*

fabrication of the prototype dispenser was completed by North American Weather Consultants under a Bureau contract. The dispenser is radio controlled via a microwave relay. Both control information and status information is communicated by radio via an on-site microprocessor. Status information includes volume of propane flow, propane tank level and spray temperature to verify actual liquid release (a temperature less than -30 °C verifies liquid spray). Three release nozzles have been mounted but only one is used at a time. If flow ceases, the back-up nozzles can be utilized. Denatured alcohol at a 3 percent by volume solution is added to each tank to minimize nozzle clogging.

Preliminary dispenser release rates have been determined. Using a single nozzle the release rates have been lowered to 11 l /hr from the 38 l/hr now currently used by the Air Force. Dispenser installation will be made in early November upon Forest Service approval and completion of the environmental reporting requirements.

It is envisioned that several different seeding techniques will be used for testing. This includes pulsed seeding (i.e. generator on for 3 hours, then off for 3 hours). Once it is established that the effects of the seeding can be observed at Johnsville, days will be established in which personnel from the Operations Control Center will determine the ON-OFF sequence of the dispensers without notifying the crew at the microphysics laboratory at Johnsville. These procedures should establish the repeatability of the seeding effects.

Phase II of this project (1989-90 winter) will include installation of ten dispensers along the Sierra Crest west and southwest of Johnsville, approximately 10 km upwind. The dispensers will be roughly 2 km apart. Assuming a 15° spread, the ice crystal plumes should be fairly continuous 10 km downstream of the dispensers. Once the effects of the seeding are determined, the statistical design will be implemented. (see Section 6.0).

Phase III would establish dispensing sites along much of the high country within the proposed target area. This would probably not occur until after the third to fifth year of the project to allow testing and evaluation of the proposed project design and allow for reduced seeding trials during wet periods when suspension criteria are invoked (Section 5.0)

4.0 SEEDING DECISION MAKING

As has been mentioned, for liquid propane to be an effective seeding agent it must be released within supercooled cloud. This will require knowledge of the presence of supercooled liquid water at the dispensing sites. These observations are being made directly through application of remote mountain icing rate stations. These stations telemeter icing occurrence, temperature, humidity, wind speed, and wind direction back through the California Data Exchange satellite downlink in Sacramento. Several icing stations are required at elevations representative of dispensing site elevations. Two sites have been established and are shown in Fig. 1. Rawinsonde sites will be located at Oroville and Johnsville. Winds and temperature will be used as input to the numerical targeting model developed as part of the SCPP. (Rauber et al, 1988).

Seeding will commence with the onset of icing. The time of icing onset might be anticipated by determining the timing of cold frontal passage across the dispensing site network. As found by Reynolds and Kuciauskas (1988) and Ryerson (1988), the onset of liquid water occurs quite frequently with or shortly after a surface or upper- level cold frontal passage. Frontal passage is closely associated with a distinct gradient in cloud top temperature as seen on infrared satellite images. Therefore, by monitoring satellite images and icing information, seeding onset time might be estimated. Seeding will be terminated when no icing has occurred for at least 2 hours. Again, satellite images will also help indicate when cloud break-up is occurring to assure conditions suitable for seeding are over.

Rawinsonde data will be monitored to assure targeting within the Feather River basin is expected via model output. This will require periodic launches at six hour intervals. Wind information from the icing stations is used between rawinsonde launches.

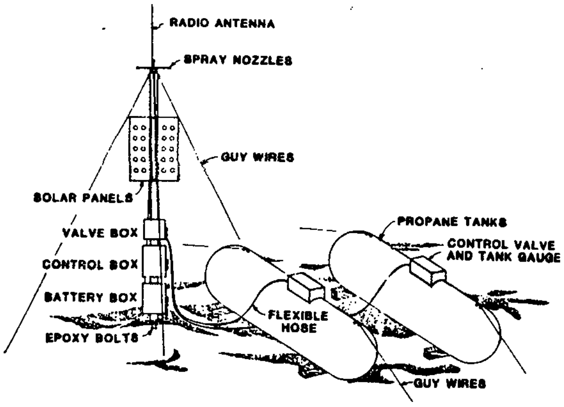

Figure 6 *Propane dispenser design and example of a typical site set-up on a mountain peak.*

5.0 SUSPENSION CRITERIA

Suspension criteria have been developed by the Flood Forecasting Section of the Department of Water Resources based on historical data indicating threshold levels when snowpack or river flow levels begin to cause concern for potential flood generations. The following sections list the criteria to be used.

1. Excess Snowpack Water Equivalent

When the water content of the snowpack in the Feather River Basin, as measured at 25 identified snow courses exceeds the accumulation envelope defined by the following percentages of April 1 average amounts on the same date:

January 1	110%
February 1	130%
March 1	150%
April 1	160%

2. Rain-Induced Winter Floods

Quantitative precipitation forecasts issued by the National Weather Service which would produce excessive runoff in the project area or downstream areas as determined by the Flood Forecasting staff of the Department of Water Resources or these conditions are observed.

a. 60,000 cfs or more inflow to Oroville Reservoir.

b. Whenever Oroville Reservoir is encroached into flood control space and releases are being made over the spillway at Oroville Dam (normally whentotal releases are in excess of about 20,000 cfs.

c. Whenever flood flows or stages are occurring or forecast to occur which exceed flood warning stages on the Feather below Oroville

(1) River stages near Gridley at or over 95 feet.
(2) River stages at Yuba City at or over 65 feet.
(3) River stages at Nicolaus at or over 43 feet.

3. Severe Weather

a. Whenever the National Weather Service has issued a flash flood warning for the project area.

4. Other Special Circumstances

The DWR Project Manager judges conditions are or may be perceived to be so hazardous as to warrant suspension of seeding. This may include the issuance of avalanche warnings within the project area.

6.0 EVALUATION

The evaluation of the snowpack enhancement program will consist of two separate efforts. The first to be emphasized during the first 3-5 years of the program, will require direct physical measurements of the seeding effects downwind of the dispensing sites (see Section 3.4). It is anticipated that these observations will lay the physical foundation for the second phase of the evaluation. This second phase is not expected to begin until after the full complement of dispensers is in place, probably after the fifth year of the project. This second phase will consist of a statistical analysis of precipitation both within the target area and in areas outside the target area and felt to be untreated. This is called a target/control evaluation method. This will require a high degree of correlation between these two locations. It is anticipated that from historical data available and with subsequent augmentation of the existing precipitation gauge network during years one through five, adequate control gauges can be established. Preliminary studies indicate as high as a .74 correlation coefficient for 3 hourly periods having precipitation between existing target and control sites. The target/control evaluation scheme will be augmented with a three to one randomization scheme. That is for every three storms seeded, one will be left as a control. The 3 to 1 ratio is used to maximize precipitation increases while still providing some control for evaluation purposes. It is envisioned this method will allow a reasonable opportunity to evaluate statistically the impact seeding has on precipitation after the second 5 years of the project.

7.0 ACKNOWLEDGEMENTS

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8.0 REFERENCES

Demott,P.J.,W.G. Finnegan, and L.O.Grant,1982: An application of chemical kinectic theory and methodology to characterize the ice nucleating properties of aerosols used for weather modification. J. Clim. Appl. Meteor.,22,1190-1203.

Deshler,T.,1988: Calibration of ice particle measurements at the ground using an aspirated 2D-C. J. Atmos. Oceanic Tech.,5,547-560.

__________,D.W. Reynolds, and J.H. Humphries, 1987: Observations of snow crystal concentration , habit, riming, and aggregation collected at the ground during six fog seeding experiments. Eleventh AMS Conference on Weather Modification, Oct. 6-8, Edmonton, Alberta, Canada. 118-121.

Heggli,M.F. and R.M. Rauber, 1988: The characteristics and evolution of supercooled liquid water in wintertime storms over the Sierra Nevada: A summary of microwave radiometric measurements taken during the Sierra Cooperative Pilot Project. J. Appl. Meteor.,27,989-1015.

Hicks, J.R. and G. Vali, 1973: Ice nucleation in clouds by liquified propane spray. J. Appl.Meteor.,12,1025-1034.

Horn,R.D., W.G. Finnegan, and P.J. Demott,1983: Experimental studies of nucleation of dry ice. J. Appl. Meteor.,21,1567-1570.

Kumai, M., 1982: Formation of ice crystals and dissipation of supercooled fog by artificial nucleation, and variations of crystal habit of early growth stages. J. Appl. Meteor.,21,579-587.

Rauber, R.M., R.D. Elliott, J.O. Rhea, A.W. Huggins, and D.W. Reynolds, 1988: A diagnostic technique for targeting during airborne seeding experiments in wintertime storms over the Sierra Nevada. J. Appl. Meteor., 27, 811-828.

Reynolds, D.W., 1988: A report on winter snowpack augmentation. Bull. Amer Meteor. Soc.,69,1290-1300.

Reynolds,D.W. and A.S. Dennis,1986: A review of the Sierra Cooperative Pilot Project. Bull. Amer. Meteor. Soc.,67,513-523.

__________ and A.P. Kuciauskas,1988: Remote and in-situ observations of Sierra Nevada winter mountain clouds: Relationship between mesoscale structure, precipitation and liquid water. J. Appl. Meteor., 27, 140-156.

Ryerson,C.C.,1988: Atmospheric icing climatologies of two New England Mountains. J. Appl. Meteor.,27,1261-1281.

Vardiman,L.,E.D. Figgins and H.S. Appleman,1971: Operational dissipation of supercooled fog using liquid propane. J. Appl. Meteor., 10, 515-525.